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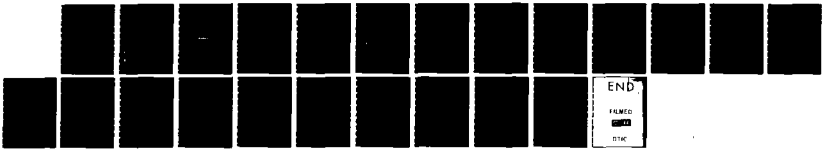

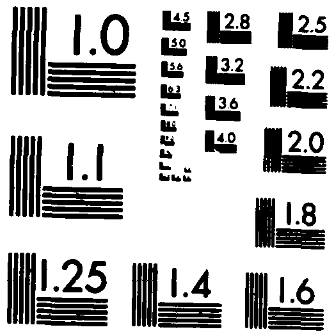

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A STUDY OF SECULAR AND TIDAL TILT IN WYOMING AND UTAH

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During the period covered by this report, we drilled ten holes at five sites in Yellowstone National Park. We designed and constructed equipment for recording tilt data at the sites and for transmitting the data to our laboratory in Boulder. We installed instruments at three of the sites and began recording data. At the same time, we began a program to analyze the tilt data using the more sophisticated Cartwright-Tayler-Edden method which allows us to explicitly extract the tidal

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Block 20. Abstract, continued.

admittance as a function of frequency. We also began a theoretical effort to model the effects of the Caldera on the earth tides. This study involved the construction of finite-element models of the area followed by calculations of the tidal amplitudes and phases at our sites as functions of the parameters of the model. This latter effort is still in progress, although we do have some preliminary results.

SUMMARY OF OBJECTIVES

1. To conduct field and laboratory measurements of long term crustal tilt at periods longer than four minutes.

2. To deploy an array of instruments in Yellowstone National Park to study the effect of the thermal anomaly on the tidal admittance.

3. To deploy an array of instruments near Ogden, Utah to study the secular tilt along the Wasatch fault zone. This is a seismically active region with a possible seismic gap near Ogden.

INTRODUCTION

At the start of the period covered by this report, we had completed an evaluation of our borehole tiltmeter design by measuring the tidal admittance at two sites near Boulder. We found good agreement between theory and experiment, and we were encouraged to proceed with the construction and installation of an array of borehole tiltmeters in Yellowstone National Park. The primary purpose of the array is to study the Yellowstone Caldera by measuring the amplitudes and phases of the earth tides at various sites. The observed amplitudes and phases should show a spatial dependence; the amplitude and phase at a given station depends on the size and shape of the magma chamber, on the elastic properties of its contents and on the position of the station relative to the magma body. The observed tides may thus be used to validate models of the Caldera.

A secondary purpose of the array is to study secular changes within the park and to compare these data with results obtained by other methods such as gravity and levelling surveys. This comparison is made more difficult by the fact that secular data are often contaminated by local effects and by the drift of the instrument. The conclusions are therefore often ambiguous. We planned to install two independent tiltmeters at each site to help resolve these ambiguities.

In this report we shall discuss the technical design of the array and some of the tools we have developed for estimating the tidal admittances at our sites and for comparing these measurements with theoretical predictions based on other studies of the region.

BOREHOLE ARRAY

The sites for the boreholes are constrained by several considerations. The holes cannot be located in hydro-thermal areas, in plain sight of tourists or far away from existing roads, power lines and telephone cables. At the same time, it is desirable to locate the holes near the periphery of the Caldera where the tidal anomaly is largest. After consultation with the National Park Service, we drilled ten holes at the following five sites: Tower Junction, Canyon Village, Lake Village, Norris Geyser Basin and Madison Junction. All of the sites are in service areas and are not far from existing telephone and power drops. In fact, telephone service has been somewhat difficult to obtain. The line at Tower Junction is extremely unreliable in the winter time. The line at Lake was installed in July, 1983, about 12 months after we asked for it; we still do not have a line at Norris. Although all sites have electrical service

nearby, the service is quite unreliable and power interruptions are quite frequent. The power lines are also quite noisy, and power transients are quite common.

Each site has two holes drilled about 3 m apart. The holes are about 30 m (100 feet) deep. We found it necessary to use double casing on most of the holes to keep them from collapsing around the drill bit. The inner casing is standard 15 cm (6 inch) diameter pipe· the outer casing is nominally 20 cm (8 inches) in diameter. The casing is purchased in random 6 m (20 foot) lengths and is welded into one continuous piece as it is inserted into the hole. The space between the inner and outer casings is filled with cement.

We installed buried cables from each hole to a nearby building. The cables are run through PVC pipe. The details vary somewhat from site to site, but the distance between the holes and the building in which the telephone and power drops are installed is usually about 30 m.

The buildings are neither heated in the winter nor cooled in the summer: we constructed wooden enclosures to protect the recording electronics and to moderate the temperature extremes. The enclosure is heated by a small thermostatically-controlled heater in the winter time and is cooled by a small fan when the inside temperature rises above about 25 C.

SITE ELECTRONICS

The electronics at each site can be divided into three categories: the components at the bottom of the hole, the components at the top of the hole and the components in the building.

The components at the bottom of the hole include two amplifiers, two phase-sensitive detectors and two output drivers. These components are located on a small circuit board placed directly above the pendulums; this configuration is unchanged from our previous installations. The outputs of this board are two d. c. voltages proportional to the tilts along the two orthogonal axes of the two pendulums in the hole. Each board is individually calibrated; the nominal calibration is 2 volts/micro-radian. These signals are transmitted to the top of the hole for filtering and digitizing.

At the top of the hole there are two single-pole lowpass filters (one for each channel), a power converter and a digitizer. These components are located on two circuit boards mounted inside a piece of PVC pipe. These components are

essentially unchanged from previous designs. The only change is the power converter, which converts 12 v d.c. to +/- 15 v d.c. Previous designs generated the bipolar 15 volts from 5 volts or directly from the a. c. mains. This change allows the tiltmeters to be run from automobile storage batteries when the power fails.

Two cables run from each hole to the enclosure in a nearby building. One cable supplies 12 v d. c. for the power converter and 5 v d. c. for the digitizer. The second cable contains two twisted pairs and is used to communicate between the digitizer in each hole and the controlling micro-computer in the enclosure. The 12 v d. c. is supplied by a storage battery which is continuously trickle-charged by a battery charger. The battery voltage is reduced from 14.6 v to 12 v using several rectifier diodes in series. These diodes provide a voltage drop of about 0.6 v each; this drop is substantially independent of load current. This configuration provides uninterrupted power to the tiltmeter in the event of a power failure. The storage battery can run the tiltmeter for about 3 days: this is adequate to deal with almost any power interruption. The 5 v d. c. is generated by a small power supply with no battery back-up. Thus no data are recorded during a power failure, although the tiltmeter itself continues to operate.

The data at each site are acquired by a micro-computer located in the enclosure. The micro-computer uses the Z80 central-processor chip. Each computer has 16 k bytes of semiconductor read/write memory (RAM), 14 k bytes of electrically-programmable read-only memory (EPROM), a clock, a serial line (RS-232) interface and a multiplexor which can interface up to 8 boreholes to the computer via a second serial interface. The various parts of the micro-computer are connected together using the S-100 bus, a hardware configuration that is a de-facto industry standard. The clock can be set under program control and automatically keeps time in standard 24-hour civil format. It has its own battery back-up so that the epoch is not lost if the power fails. The rest of the computer does not have battery backup; the power requirements are too great to run the system from batteries for even a short period of time. (This is a property of the S-100 standard and not of the Z80 system as such. The S-100 standard uses an extremely inefficient method of generating power for the operation of the computer. The power supplies dissipate so much heat that they must be forced-air cooled to keep the components below 40 C.)

The serial line is used for communicating with the system. It is usually connected to a standard telephone line via a modem so that commands may be entered remotely, but it may also be connected to a local terminal for diagnostic purposes. The modem is of the automatic answer type. It communicates at 300 baud

using frequency-shift keying. It will automatically answer the telephone line if it senses the ringing signal and will hang-up if no modem carrier is detected within 18 seconds or if the carrier is subsequently lost. Otherwise, it will never initiate a disconnect, maintaining the connection as long as the distant carrier is present. The status of the telephone line is not transmitted to the serial interface in the micro-computer, nor does the micro-computer enforce its status on the modem via RTS/CTS or DTR, for example. In this way complete symmetry is maintained between a locally-connected terminal and a distant terminal linked via the modem. It also eliminates a group of components whose failure could totally disable communications.

The final component in each enclosure is a circuit that can be used to force a hardware bootstrap of the system. (A bootstrap is a totally cold re-start of both the hardware and the software. It clears all error conditions and forces all hardware components to a known state. It clears the entire memory so that all previous data are lost. Only the time in the clock circuit is preserved.) This circuit is tone activated. When the appropriate frequency is received over the telephone line, a hardware bootstrap of the micro-computer in initiated. This circuit is needed in case the system enters an illegal state following a power transient or a nearby lightning strike.

SITE SOFTWARE

The control program at each site is contained in electrically-programmable read-only memory (EPROM) and is therefore unaffected by power failures. The program is loaded into the EPROM chips using a small development system in our laboratory in Boulder. The EPROMs may be altered by first erasing them using intense ultra-violet light after which a new program may be loaded into them. They cannot be altered in the field.

The control program is basically a single loop which executes indefinitely. Since the Z80 does not really support interrupts, the logic is implemented as a skip chain. The logical steps of the chain are:

1. Read the clock. If it is time to read the dataloggers (the dataloggers are read every 6 minutes on the even tenth of an hour), then read each channel in turn and store the values in volatile read/write (RAM) memory. Also store diagnostic information on the state of the system and perform various housekeeping chores. The number of active channels at each site and the electrical address of each channel are contained in tables in the program. If it is not time to read the dataloggers

or after the new data have been stored, then proceed to step 2.

2. Examine the status of the input serial port. If a character has been received, assume that a command is being entered. Wait for the rest of the command string, parse it and execute it. Almost all commands are handled by jumping to a command-specific subroutine. Some of the commands, such as the command to set the clock, request additional parameters. These requests are handled within the command-specific subroutine. When the subroutine returns to the main program, the main loop resumes. If no character has been received or when the execution of the requested command is finished, return to step 1.

All commands are of the form $$C<cr>. The first two characters, shown symbolically by $$, are password characters to prevent unauthorized use of the system. If they are not entered correctly, the system will not respond. The third character, shown symbolically by the letter C is a single character verb specifying the operation. The command is terminated by a carriage return. The following commands are recognized:

1. Initialize the system. This command clears all data buffers and resets various housekeeping and error variables. The time of the next scan is set to the next even tenth of an hour. The state of the hardware is not altered by this command. Otherwise it is the same as a hardware bootstrap.

2. Read the clock. Print the current time on the terminal. The time is printed in the format YYDDD HH:MM·SS, where YY is the last two digits of the year, DDD is the day number and the remainder of the time is in universal time. For example: 83212 17:55:55.

3. Set the clock. Request a date in the format YYDDD HH:MM·SS. The two digits YY are the year, the 3 digits DDD are the day number, and the remainder of the time is in universal time. The clock is set to the time as entered.

4. Scan active channels. This command sends a convert pulse to every currently active channel and prints the digitizer response on the terminal. If the digitizer does not respond, or if a format error is detected in the response, then additional diagnostic information is also printed. The digitized value is not stored. This command is intended for diagnostic purposes.

5. Enter diagnostic mode. This command requests additional parameters that can be used to run several diagnostics. These diagnostics are useful in checking the performance of the micro-computer itself and of the digitizer in each hole, and provide enough information to isolate faults at least to the

board level.

6. Enter transmission mode. This mode is used to transmit the data between the micro-computer at each site and our computer in Boulder. The protocol of this command is described below in the section on data transmission. Although this command may be entered manually, it is normally intended only for machine-to-machine communication.

7. Print diagnostic information. This comman prints the state of various housekeeping and error param ers. It is intended for diagnostic use only.

All transmissions between the micro-computer .d external devices are equipped with timers which abort the operation if it is not completed within a pre-set time interval. This feature minimizes the probability that a failure of one of the digitizers or spurious characters from the telephone line will cause the program to become stuck waiting for input that will never arrive.

DATA TRANSMISSION

The data acquired at each site are transmitted to Boulder upon receipt of the appropriate command. There is enough RAM memory at each site to store up to 90 hours of data from each active channel. A transmission is usually requested every 24 hours, so that the buffers normally never fill up.

The transmission is initiated by our PDP 11/34. Each site is assigned a unique time slot between 11 p.m. and 6 a.m. local time. The 11/34 dials each site and checks the clock at each site. If the time is incorrect, a diagnostic message is printed. If the time is correct, the command to enter transmission mode is sent. The micro-computer responds by sending the number of values currently stored followed by the data using the encoding alphabet described in our previous report. This alphabet was first developed for use in our VHF transmission link between our site at Erie and our laboratory in Boulder. It minimizes the probability that transmission errors will go undetected, and provides for unambiguous correction of many types of errors. After every 20 values, the station pauses for a status reply. If no error is signaled, the transmission proceeds with the next 20 values. If an error is sensed, the block is re-transmitted up to 5 times. After the transmission is completed without error, the final command from Boulder clears the buffer pointers. This process continues for every active channel for each site.

If a protocol error is detected, the final clear command is not sent; the telephone connection is broken and re-dialed two

minutes later and the entire process is repeated. The entire process is automated and quite reliable. The main weakness of the system is the sensitivity of the site equipment to power line transients. Such transients often cause the CPU to enter an illegal state and to essentially stop. This cannot be fixed by entering a command sequence since the parsing of such command sequences is obviously impossible. The fault condition is cleared by forcing a hardware bootstrap of the system using the tone system described above. We are working to reduce this sensitivity, but it is still troublesome.

EARTH TIDE ANALYSIS

In our previous reports, we have outlined a rather extensive set of computer programs that we use to evaluate the amplitude and phase of the tidal admittance. Although these programs are adequate as far as they go, we realized that they might not be adequate for the Yellowstone analysis. The modification of the amplitude of the earth tides by the Caldera was likely to be on the order of a few percent; a significant comparison with theory would therefore require that we our estimates of the amplitudes of the tides have uncertainties of 1% or less. We evaluated the accuracy of the existing methods using a series of simulated data sets. Each data set was generated by adding a noise time series to a time series generated using a standard earth model. The resulting data set was then processed using the techniques described in our previous reports. We would expect that all of these data sets should yield an admittance of unity, since the underlying tidal data is generated using a standard earth model. We further expect that deviations from an admittance of unity should be normally distributed, with a standard deviation that is directly calculable from the power spectrum of the noise process used to generate the test.

We found that the existing programs are most effective in dealing with high-frequency noise. This is not terribly surprising since the stochastic nature of such noise will tend to cause it to be averaged to zero with time. This is less true for low frequency perturbations, since such sources may have non-zero means over any finite analysis window. Linear drifts and annual perturbations fall into this category.

Unfortunately, it is exactly these sorts of signals that are often present in our data and are difficult to remove. The tilt signals are electrically lowpass-filtered before the digitizer. We apply additional lowpass filtering using digital techniques before the analysis. As a result, the residual high frequency noise is rather small. This attenuation coupled with the averaging properties of the analysis reduces the effect of

high-frequency noise to the point where it is no longer a significant problem.

It is more difficult to remove low frequency noise without changing the amplitude of the diurnal tides. A filter that will have ripples of less than 1% at tidal frequencies while attenuating lower frequencies by 30 db, for example, will have a transient response about one week long and will therefore be unsuitable for dealing with data that has gaps. It will also be unable to cope with noise that is almost diurnal in period, since such noise is in the passband.

After considerable experimentation, we have implemented an iterative process. The data are lowpass filtered to remove as much high frequency noise as possible. A trial tidal admittance is then calculated. The residuals of this calculation are examined. If they contain coherent tidal energy, the calculated admittance is almost certainly incorrect: the admittance calculation was contaminated with non-tidal energy at periods that are close to the tides. We then smooth the residuals by approximating them using a piecewise-continuous polynomial which reproduces the long-period shape of the residuals but does not follow the tides. These smoothed residuals are then subtracted from the raw data point by point and a new admittance is calculated using the modified data set. The process is repeated until the residuals of the admittance calculation are totally incoherent with the tidal potential. The sum of the smoothed residual functions then represents our best estimate of the secular and other non-tidal power in the record.

The success of the method depends critically on the technique used for smoothing the residuals. Our first attempt at smoothing the residuals used cubic spline functions (Forsythe et al., 1977). These functions are piecewise-continuous cubic polynomials. To construct them, it is first necessary to choose a series of data points. These are called the knots of the spline, and the spline polynomials will be constrained to pass through the knots.

We have constructed a graphical method for choosing the knots. The residuals are plotted on a large sheet of paper. The knots are chosen by hand; the time interval between knots is chosen to reproduce the non-tidal part of the residuals as closely as possible. The time interval between knots need not be a constant. Once the positions of the knots have been chosen, the coordinates of each knot are computed using a flat-bed digitizer connected to our 11/34. This procedure is extremely flexible; its success depends primarily on the experience of the user in choosing the knots and is almost totally independent of the power spectrum of the noise.

Since a piecewise cubic function uses four parameters to specify each segment, a data set of N points will have N-1 segments and therefore 4N-4 parameters. If we require that the function and its first two derivatives be continuous at the N-2 interior knots, and that the function pass through each of the knots, this is equivalent to 4N-6 conditions. We may therefore specify two additional conditions to guarantee a unique solution: traditionally, these two conditions are specified by assigning values to the second derivatives at the end-points, but other choices are possible (Ahlberg et al., 1967).

The primary weakness of splines is that the polynomial segments are not guaranteed to yield a monotonic function (even though the knots are monotonic) at places where the first derivative changes very rapidly. Traditional splines will tend to insert wiggles at such points: these wiggles are not guaranteed to be small nor can they be removed by simply increasing the density of the knots.

The monotonicity of the polynomial segments may be guaranteed using the techniques of Fritsch and Carlson (1979). We have implemented their algorithm and have found that it produces polynomials that follow the residuals much more accurately. In particular, the polynomial segments are always monotonic if the generating knots are monotonic. and rapid changes in the first derivative may be reproduced as accurately as desired by choosing the knots sufficiently close together.

The great advantage of this method is that it treats the secular tilt as a time-domain function where it often can be well characterized rather than in the frequency domain where it is usually not well defined. This process can easily deal with a secular tilt whose slope is comparable to the rate of change of the real tidal signal, for example. It is very difficult to deal with a secular change of this rate in the frequency domain, since it has appreciable power in the tidal bands.

There are, however, frequency-domain techniques which may as effective in estimating the non-tidal power in a record as our modified cubic splines. One such technique is described by Agnew (1983). He suggests that low-frequency contamination of tidal records may be removed by constructing a lowpass filter that has explicit zeroes at the known tidal frequencies. If the raw data are processed by such a filter, the output will consist of all of the power in the input record EXCEPT at the tidal frequencies where the transmission of the filter is explicitly zero. The output of such a filter is thus an estimate of the non-tidal power in the record: this power could be removed by subtracting the filter output from the raw data point by point. Agnew gives a procedure for constructing the required digital filters using a

perturbation approach that starts with a known lowpass design. This technique is guaranteed to work in principle, but we have not evaluated its performance extensively. We do not know how sensitive the depths of the notches are to roundoff errors, especially when several notches are specified simultaneously.

A second improvement was to implement a tidal admittance calculation using the Cartwright-Tayler-Edden (CTE) method (Cartwright and Tayler, 1971, Cartwright and Edden, 1973). This method expands the tides as a series of sines and cosines. The basic method has been described in our previous publications on the analysis of the strain tides (Levine, 1978).

This method has two advantages over the response-method analysis (Munk and Cartwright, 1966), which was described in our previous reports and was used in our previous analyses. The first advantage is that this type of analysis can more easily cope with contamination of the data by thermal or barometric pressure effects. Such spurious signals often have power spectra that closely resemble the tides. They cannot be removed by frequency-selective filtering. Since the response method has only four degrees of freedom in the fit (two in the diurnal band and two at semi-diurnal periods), it is unable to separate the spurious signals from the tides, with the result that the calculated admittances are always biased. The CTE method has about 28 degrees of freedom for a typical fit; thermal or barometric pressure signals are therefore correctly reported as anomalies in the solar component, which is exactly where they belong. The second advantage is that the CTE programs provide absolute admittances as opposed to the relative admittances of the response method; expanded statistical information is also provided on the standard deviations of the calculated admittances. This is not an advantage in principle, since the response method could also be used to calculate these quantities. These calculations are much simpler in the CTE method, however, and the interpretation of the results is more straightforward.

FINITE ELEMENT MODELS

An important part of interpreting the tides at Yellowstone is the modeling of the strain-tilt coupling which modifies the observed tides at our stations. This effect is caused by the lateral and vertical variations in the elastic properties of the material in the park.

We are modeling the strain-tilt coupling using finite-element models. These models are based on other studies using a variety of techniques. These models have grown increasingly sophisticated. Eaton et al. (1975), could only

describe the area as a zone of low P-wave velocity. They suggested that the observed 10% decrease in P-wave velocity might be caused by partial melting. Harrison and Flach (1976) made estimates of Poisson's ratio for the anomalous region using models in which the material contained various shapes and proportions of melt inclusions. These early calculations modeled the body as a simple vertical cylinder and suggested that the amplitudes of the tilt tides might differ from their normal values by as much as 40%.

Recent studies have provided much more detail on the crustal structure and geologic properties under the Yellowstone Caldera. Daniel and Boore (1982) used observations of teleseismic body waves and surface waves to give P-wave and S-wave velocities for normal crust compared with crust under the caldera. A combination of teleseismic P-wave velocity residuals plus an inversion of gravity data resulted in a detailed three-dimensional model of the anomalous body, shown in Smith and Christiansen (1980). This model has been updated by an even more detailed model of the velocity structure of the upper 10 km by Smith and Braile (1982).

These models have been combined to form a three-dimensional finite element model which is used to calculate the modification of the tilt tides due to strain-tilt coupling. The model consists of over 1000 elements arranged in 6 layers with the smallest elements in the center. The smallest elements are 12 km on a side horizontally and 10 km deep. The entire model is 390 km horizontally and 100 km deep. Each element of the model is characterized by Vp and Vs. The values for Young's modulus and Poisson's ratio for each element are derived from the Vp-Vs model. The parameters of the model are shown in table 1, which shows both the normal and anomalous velocities as a function of depth. The coupling between tilt and strain depends most strongly on Poisson's ratio; elements with a large Poisson's ratio therefore have the largest effect.

The effects of applying strains to the model are calculated using the ADINA (1981) program. The model is oriented NE-SW, along the longest dimensions of the caldera and the anomalous body. The distortion of the model is evaluated by applying normal compressional stresses along the principal axes of the model and one component of shear stress along a North-South axis. Each component is applied independently. The rotation method of Berger and Beaumont (1976) was used to transform the theoretical strain tides, calculated in a coordinate system oriented North-South and East-West to shear strain on the finite-element grid.

The tilts resulting from just the NE-SW compression are

plotted as a vector at each node on the surface of the grid in fig. 1. We also show the locations of our stations. The tilts shown are in response to an applied strain of 50 nano-strain, the maximum amplitude of the strain tide along this azimuth. The instantaneous tilt can be determined from this figure once the instantaneous strain is known.

The general character of the results can be easily explained. When the strain is applied, the anomalous body bulges upward and most of the induced tilt therefore points away from the center of the grid. There is, however, considerable variation in tilt direction for nodes near the caldera where there is the greatest lateral variation in elastic properties. If the anomalous region was symmetric in azimuth, the directions of the principal axes obviously become indeterminate and the induced tilt depends only on the areal strain. A shear strain would therefore not contribute to the anomalous tilt. Small changes in the model may therefore result in large changes in the calculated tilt-strain coupling factors if the changes affect the symmetry of the model without changing its average properties.

The tilt vectors shown are as large as 15% of the normal tilt tide. These tilts, however, are only one part of the coupling effect. The other normal strain component and the shear component must be added with the correct phase relationship. Although these calculations are not yet complete, our preliminary estimates suggest that the modification of the M2 tide due to strain-tilt coupling will be on the order of 10% of the normal tide. We expect this modification to depend on position and on azimuth.

Two other effects must also be added to the model before a quantitative comparison between theory and experiment is possible. These are ocean loads and local topography. Although the former is likely to vary only slowly across the array, the latter effect depends on the details of each site and will have to be evaluated using finite-element models compiled from topographic maps of the sites.

CONCLUSIONS

We have completed the design and construction of an array of boreholes in Yellowstone National Park, and we have installed tiltmeters at three of our five sites. We have acquired several months of data from each of these three sites, and we have begun to analyze it to extract the tidal admittances and the secular tilt.

We have also begun to construct finite element models of the

part to permit quantitative comparisons between our measured tidal admittances and a comprehensive theory including local geology, local topography and ocean loads. Although the models are not complete, preliminary results suggest that the correction due to local geology is about 10% of the normal tide, although it will depend on both azimuth and location.

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TABLE 1

VELOCITY MODEL USED TO ESTIMATE YELLOWSTONE STRAIN-TILT COUPLING
Velocities in km/sec

	Depth	Normal Values		Anomalous Values		
Layer	(km)	Vp	Vs	Vp	Vs	Poisson's ratio
1	0-10	6.05	3.49	4.00	1.63	0.40
2	10-20	6.50	3.58	5.70	2.47	0.38
3	20-30	6.80	3.93	6.80	3.10	0.23
4	30-40	6.80	3.93	6.80	3.51	0.32
5	40-60	8.07	4.66	7.50	4.11	0.29
6	60-100	8.07	4.66	7.50	4.10	0.29

Note: The normal value for Poisson's ratio is 0.25 independent of depth.

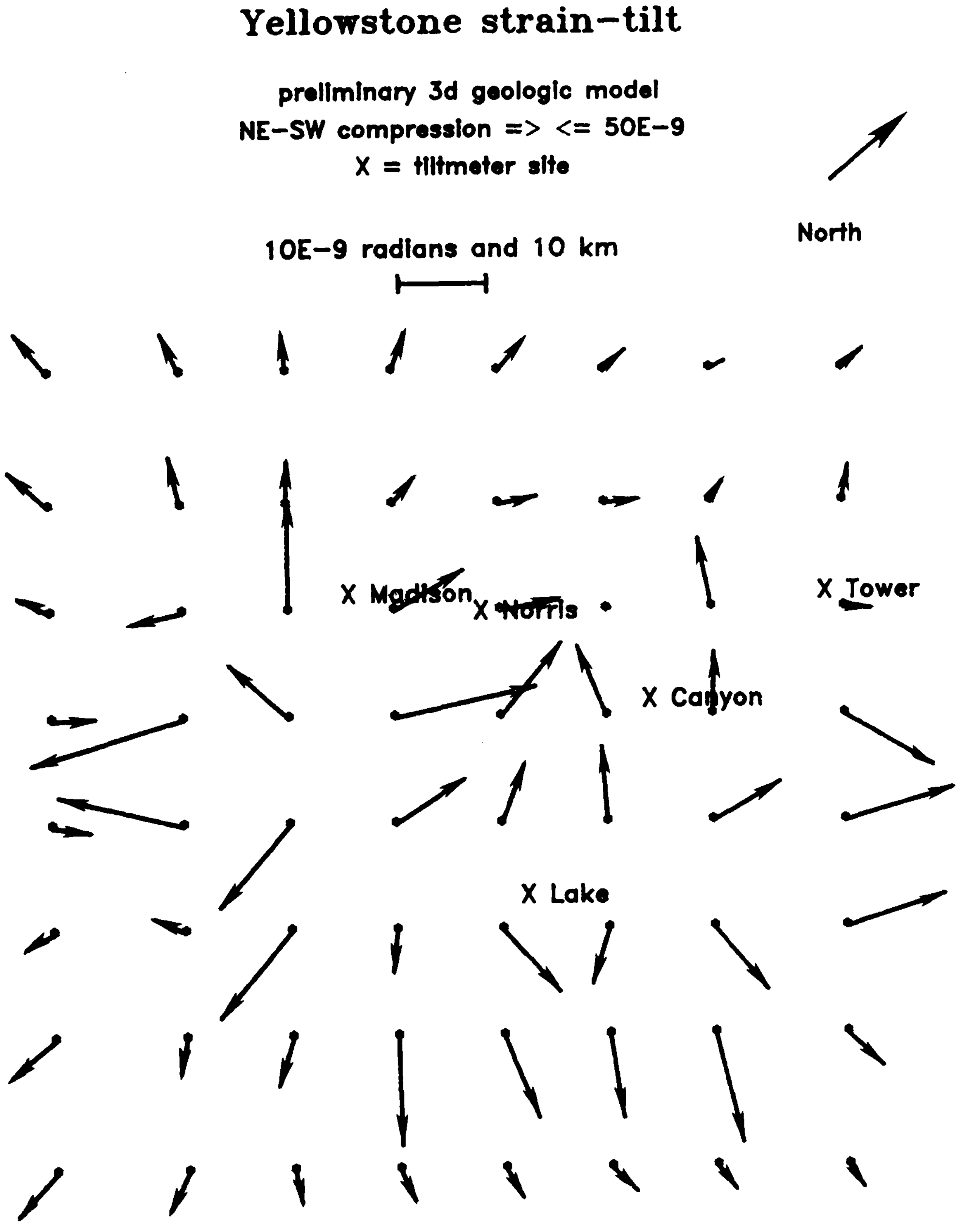

Fig. 1. Preliminary calculation of the strain-tilt coupling. The arrows show the magnitude and direction of the tilts induced at the node points of the finite element model as a result of an applied compressional strain of 50 nano-strain along the NE-SW principal axis. Also shown are the locations of the tiltmeter sites.

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